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DNF SAFETY BOARD

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The Honorable Joyce L. Connery
Chairman
Defense Nuclear Facilities Safety Board
625 Indiana Avenue NW, Suite 700
Washington, DC 20004

Dear Chairman Connery:

Over the last several years, the Department of Energy (DOE) has been working to resolve a number of technical issues regarding the Waste Treatment and Immobilization Plant (WTP), which were identified by the Defense Nuclear Facilities Safety Board (Board) and by the Office of River Protection (ORP). As documented in the Board's 2015 Annual Report to Congress, some technical issues have been resolved and others remain in progress. In 2012, ORP directed the WTP contractor to suspend design-related activities on the Pretreatment (PT) Facility and the High-Level Waste (HLW) Facility, except in areas of the HLW Facility not impacted by these issues. Since that time, DOE and the WTP contractor have performed a comprehensive set of work activities, which now provides us with sufficient confidence to direct the resumption of design activities affected by these technical issues.

The three enclosures to this letter document the details of the significant progress made to address issues associated with: 1) the generation and accumulation of hydrogen in process vessels; 2) the potential for criticality events in process vessels; 3) hydrogen in pipes and ancillary (non-process) vessels; and 4) the heat transfer analysis for process vessels. A series of analyses and engineering studies were performed that identified control strategies to demonstrate that sufficient work has been done to resume PT and HLW design and the development of safety basis documents for the areas impacted by these technical issues.

Preparation of the materials documenting the progress made on the remaining unresolved technical issues (e.g., erosion/corrosion, pulse jet mixer control) is in process and will be provided to the Board in the near future.

DOE appreciates interactions with the Board's staff on DOE's efforts to address the Board's issues. We look forward to continuing these interactions. If you have any questions, please contact Mr. Kevin Smith, Site Manager, Office of River Protection, at (509) 372-2315.

Sincerely,

Susan M. Cange
Acting Assistant Secretary
for Environmental Management

Enclosures

ATTACHMENT
TECHNICAL ISSUE RESOLUTION RECORD: RESOLUTION OF DEFENSE NUCLEAR FACILITIES SAFETY BOARD ISSUES ON WASTE TREATMENT AND IMMOBILIZATION PLANT GENERATION AND CONTROL OF HYDROGEN IN PRETREATMENT PROCESS VESSELS

Statement of Issue

In the January 6, 2010, letter from the Defense Nuclear Facilities Safety Board (DNFSB) to the U.S. Department of Energy (DOE) the following concern related to the generation and accumulation of hydrogen in Hanford Waste Treatment and Immobilization Plant (WTP) vessels mixed with pulse jet mixers (PJM) was identified (Reference 1):

> The development of a sediment layer on the bottom of tanks may reduce the effectiveness of the pulse jet mixing systems below that assumed in the design. As a result, an initially thin sediment layer could grow sufficiently to retain significant quantities of flammable gas.

In DNFSB's *26th Annual Report to Congress* (Reference 2), this concern was summarized as follows:

> Inadequate pulse jet mixing can lead to the accumulation of solids in process vessels, resulting in the generation and accumulation of hydrogen, and can potentially lead to explosions. DOE is developing a new hydrogen control strategy and associated mixing requirements. DOE is also developing a new standard vessel design that will be used for all vessels with high solids content in the PT Facility.

In the August 3, 2011, letter from the DNFSB to the U.S. Department of Energy (DOE) (Reference 3), the DNSFB highlighted concerns with the FATE™ software and associated heat transfer models used to calculate hydrogen generation rates. The letter's specific language is as follows:

> The Board's review revealed weakness in the modeling approach, assumptions, and input parameters selected by BNI for heat transfer analyses and raised concerns regarding the suitability of the Facility Flow, Aerosol, Thermal, and Explosion (FATE™) software for accurately modeling heat transfer processes in PTF process vessels.

In the *26th Annual Report to Congress* (Reference 2), this concern was summarized as follows:

> In an August 3, 2011, letter to DOE, the Board identified safety issues related to the heat transfer calculations used to establish post-accident hydrogen mixing requirements. These requirements are necessary to prevent explosions in PT Facility process vessels that will contain waste that develops distinct sludge and supernatant layers if not agitated. Due to challenges associated with pulse jet mixing, DOE is developing a new standard vessel design and a new hydrogen

control strategy with associated mixing requirements. Resolution of the heat transfer safety issue is dependent on the completion of those efforts.

Summary

The U.S. Department of Energy (DOE), Office of River Protection (ORP) agrees with the DNFSB safety concern that a sediment layer can form, upon loss of normal mixing, in PJM process vessels containing solids. The settled solids could retain radiolytically generated hydrogen gas that could be episodically released to the vessel headspace. Effective and implementable control strategies are required, and are identified, to ensure that the vessel headspace concentrations are maintained below flammable hydrogen concentration levels in both normal and off normal operating conditions.

Based on completion of a formal Engineering Study (Reference 4) that addresses the following subjects ORP considers that, for this stage of design, the hydrogen in PJM mixed vessels safety concerns identified by the DNFSB are resolved. The subjects addressed in the Engineering Study include:

- Reassessment of the functional classification of each PJM vessel consistent with DOE-STD-3009-94, *Preparation Guide for Nonreactor Nuclear Facility Documented Safety Analysis*, CN 3 (Reference 5) using conservative inputs and assumptions.
- Analysis that addressed hydrogen retention and release for the existing installed pretreatment PJM no-solids, low-solids vessels and the proposed new standard high-solids vessel (SHSV) design.
- Assessment of the impact of decay heat in settled solids and its impact on the hydrogen generation rate and hydrogen control strategy using calculations performed using the FATE™ software.
- Identification of preventative and mitigative controls for the following hydrogen release mechanisms consistent with the DOE-STD-3009-94, CN 3 and DOE O 420.1B, *Facility Safety* (Reference 6):
  - Episodic release from vessels containing high-solids waste compositions.
  - Episodic release from vessels containing low-solids waste compositions.
  - Non-episodic release from all vessels.
  - The control set accounts for settled solids, unmixed regions in the vessel and PJM body, and decay heat in settled solids. This control set is implementable and accounts for uncertainty in waste properties, waste behavior, and control effectiveness.

The proposed set of controls has been presented to the DNFSB staff for review and comment with all outstanding comments resolved.

ORP will proceed with final design and safety basis development of the Pretreatment (PT) Facility using the hydrogen control strategies presented in the Engineering Study and summarized in this Technical Issue Resolution Record. As design continues it is expected that

the selection and classification of the hazards controls will be demonstrated in the updated preliminary documented safety analysis.

Background and Previous Actions Taken

Hydrogen and other gases are continuously generated in the Hanford Site tank waste primarily through the thermal decomposition of organic compounds (thermolysis) and the radiolysis of water, and released into the WTP PJM vessel headspace. A hydrogen concentration in the vessel head space that exceeds the lower flammability limit (LFL) (i.e., 4 percent hydrogen by volume) has the potential to deflagrate or detonate in the presence of an ignition source.

Hanford slurry waste is typically categorized by its fluid yield strength as Newtonian or non-Newtonian. Newtonian fluids allow gas bubbles to rise and release into the vessel headspace as they are generated. These same Newtonian fluids may contain fast-settling solids that tend to settle out when the fluid is in a quiescent state. Those solids may form a settled-bed slurry at the bottom of the vessel covered by a layer of Newtonian supernatant. Gas generated in this settled bed tends to become entrapped, expanding as more gas is generated, and eventually breaking off as "gobs" that rise through the supernatant layer and are released in the headspace.

Non-Newtonian fluids tend to retain more gas in the slurry as its yield strength increases up to a physical threshold. When the buoyancy of the retained hydrogen overcomes the yield stress of the settled bed or non-Newtonian fluid, a sudden release of this accumulated quantity of retained gas (a larger quantity than for Newtonian fluids) may occur causing the vessel headspace hydrogen concentration to exceed the LFL for a period until the vessel headspace purge reduces the hydrogen concentration below the LFL.

The current 24590-WTP-PSAR-ESH-01-002-02, *Preliminary Documented Safety Analysis to Support Construction Authorization: PT Facility Specific Information* (Reference 7) qualitatively assumed that the unmitigated consequences of a hydrogen event in the baseline design high-solids vessels would exceed 25 rem to the public. As a result, 24590-WTP-PSAR-ESH-01-002-02 specified that safety class (SC) controls were required for mixing (PJMs and/or spargers) in order to prevent the build-up of hydrogen in unmixed waste slurries for Non-Newtonian fluids. These controls are required to meet the single failure criteria and the safety integrity level requirements of ISA S84.01-96, *Application of Safety Instrumented Systems for the Process Industries* (Reference 8).

Defense Nuclear Facilities Safety Board Letters, and the U.S. Department of Energy's Response and Subsequent Commitment

In the January 2010 letter from the DNFSB to DOE (Reference 1), the DNFSB stated that due to inadequate mixing in WTP vessels, solids may accumulate in vessels over time resulting in a sediment layer and that gas release events from this sediment layer could exceed the LFL in the vessel headspace, potentially resulting in an explosion.

In May 2010, DOE responded to the January 2010 DNFSB letter (Reference 9) and committed to resolving the identified issues with an emphasis on those related to the DNFSB concern for inadequate mixing and the potential for the formation of sediment layers. DOE specifically committed to establishing:

- Functional requirements and technical criteria for safe operation of the integrated WTP pulse jet mixing, transport, and sampling systems.
- Establishing bounding PJM design basis requirements for particle size and density based on feed qualification data; and developing design methods that demonstrate that system performance can meet functional requirements with bounding design basis inputs.

DOE further committed to:

- Adding additional PJMs to process vessels HLP-VSL-00022 and UFP-VSL-00001A/B. These vessels receive waste from the Hanford tank farms and were determined from sub-scale testing to require additional mixing power to be provided by PJMs to suspend settled solids.
- Adding vessel inspection and heel removal capability with enhanced transfer capability for 10 vessels.
- Adjusting vessel operating limits to assure adequate mixing.
- Performing integrated tests of the mixing, transfer, and PJM control systems at a larger scale.

A PJM vessel testing program and corresponding engineering assessments on vessel mixing performance were performed to resolve the concerns on PJM vessel mixing performance and resolve the previously identified External Flowsheet Review Team mixing concern (known as M3). The simulants used in the test program were representative of the WTP design requirements documented in 24590-WTP-ICD-MG-01-019, *ICD-19 Interface Control Document for Waste Feed* (ICD-19) (Reference 10) and 24590-WTP-DB-ENG-01-001, *Basis of Design* (Reference 11), which is the current design basis. The testing and analysis results presented in the engineering assessments demonstrated that solids would not accumulate in the baseline high-solids Newtonian vessel designs. The closure of these issues for the high-solids Newtonian vessels was documented in a series of closure reports (References 12 and 13). The closure reports were approved by a Technology Steering Group, which included members from both ORP and the WTP Contractor [Bechtel National, Inc. (BNI)]

The M3 reports concluded that the requirement to limit solids accumulation in the vessel was met (e.g., testing results showed no accumulation of solids) for HLP-VSL-00022 and UFP-VSL-00001A/B each of which had a distributed array of PJMs (as does the SHSV design), but could not be confirmed for the center cluster PJM and sparger design in the non-Newtonian vessels under Newtonian conditions. Subsequently, a decision was made to revise the WTP *Basis of Design* (Reference 11) to require process controls be implemented to ensure the waste in these non-Newtonian vessels be in a non-Newtonian regime (greater than or equal to 6 pascal/6 centipoise) prior to transfer out of the vessels to prevent solids accumulation (given their non-Newtonian design, the fluid needs to be in the non-Newtonian regime for the solids to be suspended and removed from the vessel during vessel pump down).

In September 2013, DOE issued the *Hanford Tank Waste Retrieval, Treatment, and Disposition Framework* (Reference 14). In this document DOE proposed to construct and operate a tank waste characterization and staging facility, which will receive, characterize, and stage high-solids streams to be transferred to WTP. The facility will include, if required, the capability to reduce the size of solids in the waste, to dissolve or blend solids, or to segregate solids from the waste stream. The actions identified and to be taken by the DOE will ensure waste delivered to the WTP complies with the waste feed specification identified in ICD-19 including the hydrogen generation rate of the waste.

Reference 14 also committed to establish a full-scale PJM vessel testing technical team and program to test PJM vessels at full scale. This testing program included a reassessment and specification of the functional and design requirements for the PJM vessels and a design for a SHSV proposed to replace the current baseline design of large volume high-solids process vessels in the PT Facility with a significantly smaller vessel volume design. The SHSV test vessel prototype has been designed, fabricated, and installed in a testing facility. Testing to demonstrate the functional performance of the SHSV is scheduled to commence in December 2016.

The proposed new SHSV design is smaller and has an enhanced mixing capability when compared to baseline WTP designs for PJM mixed high-solids vessels. Based on subscale testing and analysis, there is high confidence the SHSV design will comply with its mixing requirements, including the ability to prevent the accumulation of solids.

In the August 3, 2011, letter (Reference 3), the DNFSB provided three recommendations in relation to the thermal analysis and FATE™ software used to estimate the time to LFL in process vessels headspaces. These recommendations were to:

- Perform software verification and validation consistent with ASME V&V 20
- Perform sensitivity studies on assumptions and input parameters to determine which assumptions and input parameters have an important impact on the time to LFL
- Evaluate the need and ability to control these assumptions and input parameters during plant operations.

The DOE responded to DNFSB's letter on November 16, 2011 (Reference 15), and stated that:

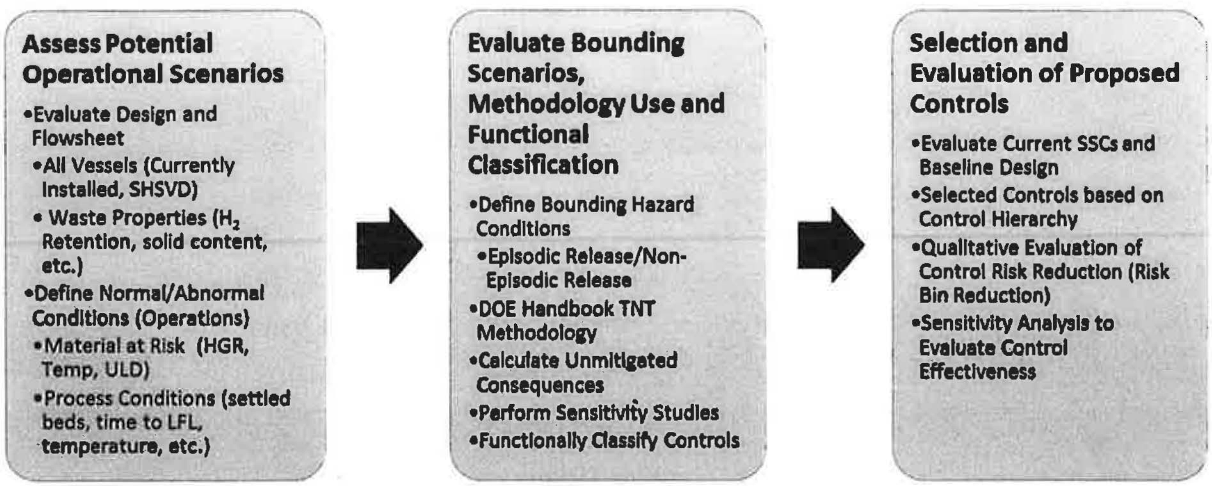
> **FATE™ Software Verification and Validation**
> WTP procedure *Acquisition and Management of Levels A, B, C, and D Software for EPCC* (Reference 3), implements V&V requirements of DOE-O-414.lC for safety software.
>
> FATE™ software has been determined to be sufficient based on its history of use, software capabilities (e.g., heat transfer), and vendor qualification.
>
> WTP agrees that the description of the model should be more clear and contain a more detailed description of conservatisms used. This includes use of additional sensitivity evaluations to clarify the conservatisms used in the FATE™ model.

Recent Actions Taken

In 2014, BNI developed a plan for the resolution of the technical issue related to hydrogen gas release from vessels. The plan was revised in 2016 (Reference 16) based on direction from ORP (Reference 17 and 18). The primary deliverable in the plan was an engineering study identifying a proposed control strategy for the control of hydrogen headspace concentrations in PJM vessels.

The methodology followed in the Engineering Study to reassess the hydrogen control strategy for PJM mixed vessels, is consistent with DOE nuclear safety philosophy as described in DOE-STD-3009-94 and DOE O 420.1B. A summary of the main work process steps and the scope of the analysis is illustrated in Figure 1.

Figure 1. Illustrative Process Used to Derive Proposed Controls.



HGR	=	hydrogen generation rate.
LFL	=	lower flammability limit.
SHSVD	=	standard high-solids vessel design.
SSC	=	structures, systems, and components.
ULD	=	unit liter dose.

Assess Potential Operational Scenarios: The WTP waste process properties and the potential for hydrogen generation and release that may result in a vessel headspace concentration higher than the LFL were evaluated:

- ***PT Facility Flow Sheet***: The bounding waste properties at each stage of the process were evaluated to determine the solids concentration, radionuclide source term, unit liter dose, and hydrogen generation rate. The proposed SHSV design parameters for volume were used for high-solids waste streams. (Note: It is ORP's plan that the baseline high-solids vessels including HLP-VSL-00022 and UFP-VSL-00001A/B identified above would be replaced by the SHSV.) The current installed vessel designs were used for the low and no solids waste streams. The evaluation considered both normal and abnormal conditions.

- ***Normal Operation***: During normal operation, vessel waste contents will be mixed with PJMs, or PJMs and spargers, causing hydrogen gas in the waste to be released into the vessel headspace. During normal operations, no sediment layer will be present during PJM pulse cycles estimated to be approximately a minute in duration. The vessel headspace will be cleared of gas using a forced air purge system operating at a purge rate of approximately 100 times greater than the hydrogen generation rate. That flowrate will maintain the hydrogen concentration in the vessel headspace below 25 percent of the LFL.
- ***Abnormal Conditions***: It is assumed that during abnormal conditions, mixing and transport operations will not be available. On loss of mixing, two scenarios are evaluated in the hazards analysis:
  - Gas is retained in the non-Newtonian waste or in a sediment layer after solids settle in the vessel and then the gas is periodically released (episodic release).
  - Gas is continuously released from the waste (non-episodic).
- ***Process Hazard Analysis***: WTP processing scenarios were used to determine a bounding hydrogen generation rate with the given waste properties of the ICD-19 waste acceptance criteria. Conservative and bounding unit hydrogen generation rates (UHGR) were chosen. Sensitivity studies were performed to demonstrate that the UHGRs selected were justified (Reference 4, Appendix C). This work included an evaluation of decay heat and its associated impact on UHGR. It concluded that ICD-19 values selected in the Engineering Study were bounding.

Evaluate Bounding Scenarios, Methodology Use and Functional Classification: The potential radiological or toxicological consequences from a hydrogen explosion were estimated using a deterministic method (i.e., the accident conditions were assumed to occur irrespective of initiating frequency, resulting in an unmitigated estimate of consequences). Upon obtaining an estimate of the unmitigated consequences for each PT Facility process vessel, the results were compared against the DOE evaluation guidelines (Reference 5) for the offsite public and the co-located worker as defined by ORP in 15-NSD-0017, "Contract No. DE-AC27-01RV14136 – Updated Safety Analysis Direction" (Reference 19). This evaluation was completed to determine if SC or safety-significant (SS) controls are required for prevention or mitigation of an accident involving a hydrogen event.

- ***Unmitigated Consequence Methodology***: The Engineering Study uses the methodology from DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, Section 3.2.2, "Explosive Stress: Shock, Blast, and Venting" (Reference 20), to quantitatively determine the unmitigated consequences for a hydrogen event in the process vessel. In the methodology from DOE-HBK-3010-94, the mass of hydrogen is converted to a trinitrotoluene (TNT) equivalent mass and then an equal mass of waste is aerosolized and released to establish the unmitigated consequences for the event.
- ***Episodic Release***: On loss of normal waste mixing, the quantity of gas that could be retained in either settled beds or non-Newtonian slurries was calculated using the limiting intrinsic capacity of the waste to retain hydrogen based upon testing of Hanford tank

waste conducted by Pacific Northwest National Laboratory (i.e., 35 percent of hydrogen gas by volume). The retained gas generated in the waste is independent of time. This volume of gas was then assumed to be instantaneously released into the headspace of the vessel in a stoichiometric mixture with nitrous oxide (Reference 4, Appendix D).

- ***Non-Episodic Release***: On loss of headspace purge, it was assumed hydrogen would be continuously evolved into the headspace of the vessel for 1,000 hours (a sensitivity analysis up to 5,000 hours was performed to assess fully unmitigated consequences) and at all times the gas in the headspace of the vessel was in a stoichiometric mixture with nitrous oxide. A bounding hydrogen generation rate is assumed (Reference 4, Appendix D).

Selection and Evaluation of Proposed Controls: Current controls and structures, systems, and components (SSC) were evaluated during the control identification process. The study discusses the significance to safety of the SC/SS SSCs. Additionally, the unmitigated risk (i.e., before application of proposed controls) and mitigated risk (i.e., after application of controls) are qualitatively estimated and presented using conventional "risk" binning matrices to illustrate the potential effectiveness of the proposed controls using the evaluation criteria and method established in 15-NSD-0017 (Reference 19). The final set of proposed controls is provided in Table 1. Additionally, several additional analyses were completed to support the proposed controls set, these include the following:

- ***Evaluate the SHSV design and existing SSCs to withstand a hydrogen ignition event***: An evaluation was performed for the SHSV and process vessel vent exhaust system (PVV)/pretreatment vessel vent process system (PVP) to determine how the systems would be impacted by a bounding episodic hydrogen release and ignition event. This analysis included structural analysis as well as calculating temperatures and pressures that equipment would experience from the event. Design changes were proposed if the analysis was shown to exceed design requirements.
- ***Control effectiveness***: Two sensitivity studies (Appendices L and M of Reference 4) were performed to determine effectiveness of sparging and its impact to time to LFL (to establish timing, flowrate, and duration). This evaluation considered that there is a possibility undisturbed regions could exist at the bottom of a SHSV even when sparging was performed at the design flow rate. The results of this study indicate a need to control batch volume, hydrogen generation rates, and/or waste properties (see Reference 4, Appendix M [Table 8] and the Appendix D addendum, Table 8-2). These waste process/waste parameters could be implemented as part of the batch processing plan's specific administrative control (SAC).

Table 1: Proposed Controls for Pretreatment Facility. (2 pages)

Hydrogen Release Mechanism	Preliminary Functional Classification		Preventive Structures, Systems, or Components	Mitigative Structures, Systems, or Components
	Safety Class	Safety-Significant		
CS-1a. Episodic Release in High-Solid PJM Vessels	All High-Solids Vessel and related SSCs	None	SHSV Vessel spargers and SAC for sparger operation Active ventilation of vessel headspace • PVV/PVP • Forced air purge SAC on waste acceptance criteria SAC for batch processing plan (e.g., batch volume/liquid level, temperature, decay heat, UHGR) SAC for PJM restart	Vessel for confinement PVV/PVP for confinement and filtration Facility structure (e.g., cell) and C5V for confinement and filtration
CS-1b Episodic Release in Low-Solid PJM Vessels	None	Low-Solid Installed Vessel (e.g., FRP-VSL-00002)	Active ventilation of vessel headspace • PVV/PVP • Forced air purge SAC for batch processing plan (e.g., batch volume/liquid level, temperature, UHGR) SAC on waste acceptance criteria SAC for PJM restart	PVV/PVP for confinement and filtration Facility structure (e.g., cell) and C5V for confinement and filtration

Table 1: Proposed Controls for Pretreatment Facility. (2 pages)

Hydrogen Release Mechanism	Preliminary Functional Classification		Preventive Structures, Systems, or Components	Mitigative Structures, Systems, or Components
	Safety Class	Safety-Significant		
CS-2 Non-Episodic Release in All PJM Vessels	Some High-Solid Vessels	Some High-Solid Vessels Some Low-/No-Solid Vessels	SHSV and other PJM process vessels Active ventilation of vessel headspace • PVV/PVP • Forced air purge SAC on waste acceptance criteria SAC for batch processing plan (e.g., batch volume/liquid level, temperature, decay heat, UHGR) SAC for PJM restart	PVV/PVP for confinement and filtration Facility structure (e.g., cell) and C5V for confinement and filtration

C5V = facility containment ventilation.
PJM = pulse-jet mixed.
PVP = process vessel vent exhaust system.
PVV = pretreatment vessel vent process system.
SAC = specific administrative control.
SHSV = standard high-solids vessel.
SSC = structures, systems, and components.
UHGR = unit hydrogen generation rate.

Discussion

Proposed Control Strategy

The proposed control strategy in the Engineering Study is consistent with DOE nuclear safety philosophy as described in DOE-STD-3009-94 and DOE O 420.1B (Reference 6). Based on the waste characteristics, two control strategies are proposed upon a loss of normal vessel mixing operations for PJMs in all vessels and PJM and air spargers in the SHSV design. These control strategies are described below. Table 1 provides an overview of the SSCs and their functional classification.

In addition to the preventative control strategies described below, the C5V, PVV/PVP, and facility structure provide SC confinement.

Control Strategy Number 1 (Episodic Release) (CS-1a, CS-1b)

High-Solids Newtonian and Non-Newtonian Waste: A SAC is proposed to ensure safety sparging is performed on a schedule less than the time required to accumulate a gas volume in the waste that, if instantaneously released, would result in the vessel headspace hydrogen concentration exceeding the LFL (4 vol% hydrogen). The spargers and the SAC comprise the primary preventive controls for controlling hydrogen release into the vessel headspace. An independent and redundant SC compressed air system would provide the air supply for the sparging operation. The actual timing, flowrate, and duration for sparging are to be developed in design and will consider the impact of decay heat on the UHGR. Analysis/Testing results indicate that in 1 hour (or less depending on the sparge flowrate), the hydrogen concentrations in the waste could be reduced by at least 50 percent by sparging. Retention and release characteristics of the sparged waste will be an important consideration for development of the SACs.

In addition to sparging, a SC forced air purge and the SC PVV/PVP will be provided as a separate control to ensure the vessel headspace concentration of released hydrogen is maintained below the LFL. This is proposed because while it is expected that the sparging process (spargers with an implementing SAC) should be sufficient to prevent exceeding the LFL in the headspace of SHSVs, an increased air flow from the forced air purge and/or PVV/PVP will provide significant defense-in-depth to control the headspace hydrogen concentration. As such, increased vessel sparging (and increased purge if needed) would be implemented to maintain the hydrogen concentration in the headspace to less than the LFL. This will prevent the hydrogen event and protect the assumption of the vessel and PVV/PVP operability as a credited primary confinement barrier. The details of the actual timing, durations, and flow rates would be developed as a follow-on engineering design process for these SSCs.

A SAC for the waste acceptance criteria has been identified to maintain assumptions associated with the as-received condition of the waste from the Hanford tank farms (e.g., the waste UHGR), which could affect process-related controls (e.g., sparging timing, duration, and flowrate). A second SAC for a batch processing plan has also been identified to control aspects of operations in the PT Facility after waste receipt. Features of the batch process plan could include controls on the vessel volume or temperature to maintain certain hydrogen generation rates.

Low-solids Newtonian Waste: The low-solids installed vessels are expected to contain no solids to low solids (up to 5 wt% undissolved solids). In the upper range of undissolved solid concentrations with a prolonged period without PJM operation, a settled layer may form sufficient in depth to retain, then release, a quantity of hydrogen gas in excess of the LFL of the headspace. To prevent this condition, the PJMs will be required to be periodically operated to mobilize settled solids and release the retained gas. In addition, an administrative control (as part of the batch processing SAC) could be required to control the batch volume and/or composition control. This control is not expected to be required for all waste feed batches.

Similar to CS-1.a in Table 1, a SAC for the waste acceptance criteria would be used to maintain assumptions associated with the as-received condition of the waste from the Hanford tank farms (e.g., the waste UHGR). Additionally, SC forced air purge and/or the SC PVV/PVP is available to ensure the vessel headspace concentration of released hydrogen is maintained below the LFL.

Control Strategy Number 2 (Non-Episodic Release) (CS-2)

It was concluded that the existing control strategy for PJM vessels, which contain Newtonian waste (that releases hydrogen non-episodically) be maintained. The control strategy requires a safety credited vessel forced air purge and PVV/PVP to provide a continuous airflow across the vessel headspace. For those process vessels where the hydrogen generation rates are low (i.e., greater than 1,000 hours required to produce sufficient hydrogen to be above the LFL), the current safety requirements document design criteria would be applied (i.e., no safety controls required for vessels that do not generate hydrogen levels above LFL within 1,000 hours and the unmitigated consequence analysis would not drive SC controls).

In addition to the two control strategies above, an administrative control may be required on PJM restart to protect the headspace concentration from the hydrogen built up in a quiescent PJM tube due to the discontinuation of normal operations in which the PJMs are periodically operated. This administrative control will be evaluated during design.

Commitments made related to Access Ports and Heel Removal

In the May 17, 2010, letter from the DOE to the DNFSB (Reference 9), DOE made commitments to add vessel inspection and heel removal capability. In combination with the control set described above and the proposed SHSV design as a replacement for certain vessels to improve mixing and transfer capabilities, these commitments are no longer required.

Heat Transfer and FATE™ Software

The decay heat analysis used in the Engineering Study continues to use the FATE™ software as identified in the DOE response to the DNFSB on August 3, 2011 (Reference 3). However, the UHGRs calculated using the FATE™ thermal analysis were not used as the basis for establishing functional classification of the safety controls in the study. Vessel UHGR values used in the study were based on ICD-19 limits, adjusted where necessary to reflect process conditions of concentration and temperature in the PT Facility. The temperature profiles and associated UHGRs calculated using FATE™ software were compared against the conservative limits used in the study to assess decay heat effects and to provide assurance that the parameters used were bounding. The proposed control strategy crediting the sparging, the SAC to implement sparging, and forced air purging and operating PVV/PVP to ensure waste temperature gradients will tend to converge toward an average bulk waste temperature dependent on the sparge airflow and duration. However, the cooling effects of evaporative cooling from sparging and/or forced air purge were not credited or considered in the analysis. It should also be noted that the significantly smaller SHSV design will have increased cooling capability due to significant decrease in vessel diameter. By not crediting these effects the analysis provided assurance that the UGHR values are sufficiently bounded and decay heat effects need not be considered in the functional classification of the controls.

Recent Interactions with Defense Nuclear Facilities Safety Board Staff

On August 22, 2016, ORP provided the Engineering Study to the DNFSB staff for review. The DNFSB staff subsequently provided a series of questions, which were addressed at an onsite briefing on October 4, 2016 (Reference 21). Based on discussions from that briefing, several subsequent teleconferences were held to address and resolve additional questions and comments. As a result, ORP provided four additional assessments (appendices to the Engineering Study) that:

- Addressed the potential for hydrogen accumulation in settled beds in currently installed PJM Newtonian vessels (Reference 4, Appendix K).
- Summarized an evaluation of postulated unmixed regions within the SHSV design considering sparger operation only. This was done to assess the potential impact from the vessel headspace hydrogen concentration with an episodic release from sediments in unmixed regions in the vessel (Reference 4, Appendix L).
- Presented an evaluation of the maximum gas retained in settled beds in non-Newtonian slurry (Reference 4, Appendix N).
- Evaluated the impact of hydrogen retention in PJMs and the need of a PJM restart strategy (Reference 4, Appendix M).

The Engineering Study was subsequently updated and re-approved based on these assessments to modify the proposed hydrogen control strategy. The final Engineering Study and briefing for the DNFSB staff was provided on November 4, 2016.

Conclusions

ORP agrees with the DNFSB safety concern that a sediment layer can form, upon loss of normal mixing, in pulse jet mixed process vessels containing solids. The settled solids could retain radiolytically and thermally generated hydrogen gas that could be episodically released to the vessel headspace. Effective and implementable control strategies are required, and are identified, to ensure that the vessel headspace concentrations are maintained below flammable hydrogen concentration levels in both normal and off normal operating conditions.

Based on completion of the Engineering Study, ORP considers that, for this stage of design, the hydrogen in PJM mixed vessels safety concern identified by the DNFSB is resolved.

The Engineering Study provides the basis for derivation of preventative and mitigative controls for the following hydrogen release mechanisms consistent with the DOE-STD-3009-94 and DOE O 420.1B:

- Episodic release from vessels containing high-solids waste compositions.
- Episodic release from vessels containing low-solids waste compositions.
- Non-episodic release from all vessels containing solids.
- Control set accounts for settled solids, unmixed regions in the vessel and PJM body, and decay heat in settled solids. This control set is implementable and accounts for waste properties, waste behavior, and control effectiveness.

ORP will proceed with the final design and safety basis development of the PT Facility using the hydrogen controls strategies presented in the Engineering Study and summarized in this Technical Issue Resolution Record. As design continues it is expected that the adequacy of the hazards analysis and the selection and classification of the hazards controls will be demonstrated in the preliminary documented safety analysis.

Concurrence

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ATTACHMENT 1
RESPONSE TO THE DEFENSE NUCLEAR FACILITIES SAFETY BOARD ISSUE: POTENTIAL FOR INADVERTENT CRITICALITY

Statement of Issue

The Defense Nuclear Facilities Safety Board (DNFSB) identified the following safety issue related to criticality safety in Waste Treatment and Immobilization Plant (WTP) vessels mixed with pulse jet mixers (PJM) (Reference 1):

> Dense particles rich in plutonium and uranium are expected to settle preferentially on the bottom of tanks. These settled particles may form a sediment layer with sufficient fissile mass in a geometry such that a criticality accident is credible. Furthermore, if the vessels are not well mixed, samples drawn from the vessels to ensure that such an event does not occur will not be representative.

In the DNFSB *26th Annual Report to Congress* (Reference 2), this concern was summarized as:

> Criticality in Process Vessels—inadequate pulse jet mixing could lead to the accumulation of fissile material at the bottom of WTP process vessels, and potentially lead to criticality. Particles of fissile material could separate from neutron absorbers and reach a critical mass in WTP process vessels. The WTP contractor conducted engineering studies and hazards assessments to evaluate criticality safety hazards and potential controls for the vessels with high solids content in the PT and HLW Facilities.

Summary

ORP agrees with the DNFSB concern that, at the time of identification in 2010, the WTP Project had not completed sufficient analysis and design development to fully understand the criticality issue in WTP. Since that time a comprehensive set of work activities was performed to evaluate this nuclear safety issue and identify feasible WTP operating and control strategies to treat the associated tank waste materials.

Based on completion of the following actions, ORP considers that the criticality safety concern identified by the DNFSB is resolved:

- Assessments to estimate the mass, particle size and location of heavy plutonium particulate (HPP) in the Hanford tank farm (HTF).
- Chemistry studies, criticality calculations, and hazards analyses, demonstrating that the co-precipitated plutonium waste form can be safely processed in WTP.
- Engineering study with supporting analyses identifying proposed controls for treatment of waste containing HPP in the Pretreatment Facility.

- Identification of proposed controls identified in the WTP Criticality Safety Evaluation Report (CSER) and the Criticality Safety Evaluation Engineering Study (CSE-ES) for management of tanks wastes containing fissile material, considering both uranium and plutonium.
- Independent review by the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program Criticality Safety Support Group (CSSG) on the proposed control strategy for treatment of HPP containing wastes.
- Commitment to deliver waste feed to the WTP complying with the design basis.
- Evaluation of an improved PJM vessel design that will improve mixing performance and the ability to effectively remove heavy solids.

The DOE Office of River Protection (ORP) will continue to complete final design and safety basis development of the WTP. This will include an update to the design basis to incorporate HPP as a waste feed component.

Background and Previous Actions Taken

Fissile Material Inventory and Characterization

From 1943 to 1988, weapons grade plutonium was produced at the Hanford Site. By the nature of the processes involved, significant quantities of fissile material were produced with the residual materials transferred to HTF as waste. This waste will be retrieved and will eventually be immobilized by vitrification in the WTP. The vast majority of this fissile material (approximately 554,000 kg) is classified as slightly depleted uranium. This material, with no dependence on particle size, is not capable of sustaining a fission chain reaction in the HTF or WTP (Reference 3). The remainder of the fissile material at the HTF is plutonium (approximately 770 kg), and is dominated by the isotope plutonium-239 (approximately 726 kg), which is the primary material of criticality concern at WTP facilities. Due to the fact that the majority of plutonium in the HTFs is co-precipitated with absorber materials (e.g., iron, nickel, manganese), the majority of waste will remain subcritical under all process and physical conditions at WTP.

Currently, criticality safety at WTP is ensured by compliance with two criticality controls; these are the plutonium/metals ratio and the fissile uranium/total uranium ratio in the waste received from the HTF and as specified in the WTP Waste Acceptance Criteria (WAC) (Reference 4). A criticality accident is not considered credible when the waste meets these two conditions. This waste contains plutonium co-precipitated with metal oxide particles bound in crystalline structures constituting the majority of the plutonium form (approximately 740 of the 770 kg).

In January 2010 (Reference 1), the DNFSB identified that there is potential for gravitational segregation of HPP from the bulk waste during PJM operation. If sufficient HPP were to accumulate in a process vessel, an inadvertent criticality event could occur. In addition, the DNFSB staff identified that it would be "practically impossible to obtain reliable measurements of local solids concentration by sample withdrawal." The CSSG reaffirmed these concerns in March 2010 (Reference 5). The CSSG also identified a concern that fissile material could potentially separate from neutron absorbers and reach a critical mass in WTP process vessels during the operation of PJMs. The DNFSB also asserted that sodium diuranate and related uranium minerals could also segregate and accumulate and pose a potential for inadvertent criticality event. However, uranium at the HTF, no matter its physical characteristics, has been determined not to pose a criticality hazard at WTP due to its inherent low enrichment. This was communicated to the DNFSB via letter (Reference 6).

In 2010, BNI Criticality Safety staff completed a study of the historical information on plutonium solids entrained in Hanford Plutonium Finishing Plant (PFP) aqueous waste. The study, completed in June 2010 (Reference 7) summarized a review of available data and records concerning discards of plutonium liquid wastes from the PFP, particularly as related to the concerns identified by the DNFSB about plutonium quantities, particle sizes, and particle densities. The study conclusions resulted in the issuance of a potential inadequacy in the safety analysis (PISA) to the Documented Safety Analysis for the HTF (Reference 8). To resolve the PISA, a second team of experts lead by the HTF contractor was tasked to characterize and conservatively estimate the HPP inventory.

In October 2011, the HTF contractor issued a report documenting plutonium oxide receipts into the HTF (Reference 9). This report provided a conservative inventory and particle size estimate for the HPP. It provided an estimate that up to 30 kg of HPP (both plutonium oxide and plutonium metal fines) having particle sizes between 10 and 100 micron, may have been transferred to 16 Hanford tanks from operations at PFP (Reference 9). These 16 tanks are included in the WTP waste feed basis, but plutonium particles in excess of 10 microns in diameter are not currently included in WTP's WAC (Reference 4) and the WTP *Basis of Design* (Reference 10).

Based on the conclusions of RPP-RPT-50941 (Reference 9), the BNI requested ORP provide direction regarding a potential change to the WTP design criteria to include the treatment of HPP in the WTP feed (Reference 11). In March 2012, ORP directed that WTP evaluate the impact on criticality safety if HPP were to be treated in WTP, but stated that the existing WTP design basis was not being changed by this direction (Reference 12). In December 2012 the Secretary of Energy requested an independent review team (IRT) to review the criticality strategy at WTP. In 2013, the IRT documented their recommendations in CCN: 261324 (Reference 13).

DOE Response to DNFSB Letter (Reference 6)

In May 2010, DOE responded to the original DNFSB letter and committed to resolving the identified issues. DOE specifically committed to:

- Establishing functional requirements and technical criteria for safe operation of the integrated WTP pulse jet mixing, transport, and sampling systems

- Establishing bounding PJM design basis requirements for particle size and density based on feed qualification data
- Developing design methods demonstrating that system performance can meet functional requirements with bounding design basis inputs
- Establishing a criticality safety strategy reflecting the capabilities of the mixing, transporting, and sampling systems.

DOE further committed to adding additional PJMs to the HLP-VSL-00022 and UFP-VSL-00001A/B vessels to improve their mixing capability to mobilize and suspend solids, adding vessel inspection and heel removal capability with enhanced transfer capability for 10 vessels; adjusting vessel volume operating levels to improve PJM mixing power to assure adequate mixing; and performing integrated tests of the mixing, transfer, sampling, and PJM control systems at a larger scale.

ORP is currently evaluating a revised PJM vessel design termed the standard high-solids vessel (SHSV) that is significantly smaller in volume with improved mixing performance capability. These vessels may be used to replace a number of vessel designs in the Pretreatment Facility, including those vessel designs identified above.

Many of the commitments made in the May 2010 letter to the DNFSB (Reference 6), were previously addressed in the testing program and vessel assessments performed to close the External Flowsheet Review Team[1] (EFRT) mixing concern [Major Issue 3 (M3), inadequate design of PJM mixed vessels)]. The EFRT issue was stated as:

> Issues were identified related to mixing system design that will result in insufficient mixing and/or extended mixing times. These issues include a design basis that discounts the effects of large particles and of rapidly settling Newtonian slurries. There is also insufficient testing of selected designs.

The M3 test program scope included testing of a number of prototype WTP vessel designs at small scale to assess their mixing capabilities using test data and scaling relationships. The resolution of M3 vessel mixing performance issue was documented in a series of engineering reports (References 14, 15, and 16). While these reports supported resolution of issues associated with the Newtonian vessels, they did not include resolution of the mixing issues associated with non-Newtonian vessel designs.

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[1] The External Flowsheet Review Team was a group of 31 reviewers charted by Bechtel National, Inc. to challenge the design of the Waste Treatment and Immobilization Plant. The team identified 17 main issues; M3 was associated with the inadequate design of the pulse jet mixers mixed vessels. The team's report reference is attached to CCN: 132846, 2016, "Report of External Flowsheet Review Team for the Hanford Tank Waste Treatment and Immobilization Plant-Final Report Titled: "Comprehensive Review of the Hanford Waste Treatment Plant Flowsheet and Throughput"" (external letter to R.J. Schepens, Office of River Protection), from J.P Henschel, Bechtel National, Inc., Richland, Washington, March 17.

Hanford Tank Waste Retrieval, Treatment, and Disposition Framework (Reference 17)

HTF waste feed to WTP is required to be compliant with the WAC specified in ICD-19 (Reference 4). In order to improve the HTF capability to achieve this requirement, DOE has proposed to construct and operate the Tank Waste Characterization and Staging Facility (TWCSF), which will receive, characterize, and stage high solids waste streams to be fed to WTP. TWCSF may include, if required, the capability to reduce the size of solids in the waste, to dissolve or blend solids, segregate solids from the waste stream or add absorbers to address criticality concerns (for plutonium oxide and metal). TWCSF would increase the assurance that the waste delivered to the WTP will comply with the WAC.

The framework document (Reference 17) also committed to establishing a full-scale PJM vessel testing technical team and program to test PJM vessels at full scale. This testing program will include confirmatory testing, at full scale, the SHSV design proposed to replace eight vessels containing solids concentrations greater than 5 wt% having both Newtonian and non-Newtonian fluid conditions. The SHSV design has been developed and procured, and testing of this vessel will commence in December 2016.

Recent Actions Taken to Evaluate Criticality Concern

In May 2014, ORP provided further direction to Bechtel National, Inc. (BNI) to plan for the authorization to proceed with Pretreatment Facility engineering, procurement, and construction activities (Reference 18), including resolution of criticality safety issues. This letter of direction was subsequently updated in May 2015 (Reference 19). In response to these letters of direction, BNI issued the *Plan for Resolution of Criticality Technical Issues* (Reference 20). This plan required a CSE-ES to be prepared for waste containing HPP. Additionally, the plan required a revision of the WTP Preliminary CSER for waste that does not contain HPP to resolve outstanding conditions of approval (COA). The specific products, scope, and objectives of each of these two documents and supporting reports are as follows:

- Chemistry Studies:
  - To support both the CSE-ES and the WTP CSER revision, three chemistry reports were produced that evaluated WTP processes, effects influencing plutonium – absorber interactions and distributions in routine, and upset WTP operations (Reference 21, 22, and 23). These chemistry studies were used to support two criticality hazard assessments (for the Pretreatment and High-Level Waste facilities) and fulfil recommendations from the CSSG, IRT, and ORP. These reports provided the basis to resolve several open items tied to the WTP Preliminary CSER and demonstrated that the co-precipitated plutonium forms would remain stable in chemical physical environments anticipated within the WTP. The results of these chemistry studies were presented to DNFSB staff on April 16, 2015, and October 28, 2015.

- Fluid Dynamics Study:
  - To support the CSE-ES, a study was completed to evaluate the impact of SHSV PJM operation on potential HPP particle geometries (Reference 24). These geometries were based on first principles and included a sediment layer/bed (lens shape) on the tank bottom surface with an estimated safe critical mass limit of 16 kg plutonium oxide and a vertical fluted horn located in the center of the tank bottom having an estimated safe mass limit of 2.7 kg plutonium oxide. The fluted horn geometry could only occur when all PJMs are operated simultaneously in an idealized operating condition. When PJM mixing stops, the vertical fluted horn configuration is expected to give way to a flattened and less critical configuration resulting in an increase to the critical mass limit. Results of the Fluid Dynamics Study were presented to DNFSB staff on October 28, 2015.
- Criticality Hazard Assessment:
  - To support both the CSE-ES and the WTP CSER revision, formal hazard assessments were conducted for the Pretreatment and High-Level Waste facilities to support the CSE-ES and CSER (References 25 and 26). These hazard assessments fulfil recommendations from the CSSG, IRT, and ORP. Results of the hazards assessments were presented to DNFSB staff on October 28, 2015.
- Criticality Calculations:
  - To support the CSE-ES, criticality calculations were performed on the bounding geometries described in the Fluid Dynamics Study, to derive bounding HPP safe mass limits for various process conditions (Reference 27). Results of these calculations were presented to DNFSB staff on October 28, 2015.
  - To support the WTP CSER revision, calculations were prepared (Reference 28) and used to derive the current criticality controls for waste not containing HPP (e.g., co-precipitated plutonium and uranium).
- CSE-ES for HPP:
  - The CSE-ES was prepared to evaluate waste compositions that contains HPP (Reference 29). This evaluation was documented as an engineering study and proposed controls to implement the double contingency principle as the preferred criticality control strategy as described in DOE O 420.1B, *Facility Safety* (Reference 30). The evaluation determined that the proposed controls could be implemented into either the current Pretreatment Facility design or a design that includes the SHSV. The proposed controls for treatment of waste containing HPP credit the use of soluble neutron poisons and removal of waste solids from the vessel.
  - The CSE-ES is considered to be an initial evaluation of criticality safety associated with HPP in the WTP. Additional evaluation and development of the control strategy will be required following additional development of waste feed staging and associated waste compositions from the HTF.

- The results of this study were presented to DNFSB staff on October 28, 2015.

- Revised Preliminary CSER:
  - The WTP Preliminary CSER addresses waste containing uranium and co-precipitated plutonium. The Preliminary CSER was revised to resolve outstanding conditions of acceptance (Reference 3). The two controls were derived in the CSER (i.e., plutonium/metal ratio and fissile uranium/total uranium ratio) and can be implemented into either the current Pretreatment Facility design or a design that includes the SHSV. The controls do not credit mixing or sampling within WTP. The Preliminary CSER was presented to the DNFSB staff on October 28, 2015.

In March 2016, BNI submitted the Preliminary Co-Precipitated Plutonium CSER to ORP (Reference 30). This CSER addressed all open COAs and CSSG issues at that time. In June 2016, ORP approved the CSER based on four COAs (Reference 32). The changes to the CSER to address these COAs were completed in September 2016 (Reference 33).

In April 2016, BNI submitted the completed CSE-ES to ORP (Reference 34). This was subsequently accepted by ORP with the acknowledgement that the study satisfactorily addresses the extent to which HPP can be safely processed in the Pretreatment Facility (Reference 35). It should be noted that at this time, ORP has not directed a change to the WTP design basis and ICD-19 to allow the receipt of HPP into pretreatment.

Several DNFSB staff briefings for this issue have been conducted to ensure the staff were current with work being performed and allow the opportunity to provide and/or resolve any questions or concerns. Specific briefings with the DNFSB staff included:

- October 15, 2014 – Criticality Resolution Plan (e.g., Criticality Resolution [T2] Plan and Presentation)
- April 16, 2015 – Criticality Chemistry Study Briefing
- October 28, 2015 – Pretreatment Criticality Strategy, Hazards Assessment, Criticality Chemistry Studies, Fluids Dynamics Study, Criticality Engineering Study
- October 5, 2016 – Criticality Resolution Briefing: The WTP Project received a set of lines of inquiry, generally pertaining to HPP characterization and related chemistry conditions that were addressed (Reference 36).

Since the October 5, 2016, briefing, no new lines of inquiry have been received from the DNFSB staff.

Discussion

ORP considers the issues as identified by the DNFSB associated with criticality safety in PJM vessels resolved considering the summary in the following sections.

Feed Control to WTP

The following DNFSB concern has been addressed in the WAC in ICD-19 and the WTP approved *Basis of Design* (Reference 10):

> The Board found deficiencies in the functional requirements for mixing and transport systems; specifically, the requirements do not adequately bound the properties of waste to be processed.

ICD-19 requires the HTF contractor to provide a sample of the staged waste feed to the WTP operating contractor at least 180 days in advance of the expected waste feed transfer date to the WTP. This sample will be required to demonstrate compliance with the ICD-19 WAC prior to transfer of waste to WTP being authorized. ORP has also proposed that the TWCSF will be used to supplement current tank farm capabilities to meet the requirements of sampling, characterization, and conditioning of the tank farm waste before transfer to the WTP.

With respect to HPP, this material is currently tracked by the HTF contractor. The HTF contractor cannot transfer this material, and subsequently the tank, in which this material resides to WTP until a control strategy for this material is implemented.

Even though waste with plutonium particles greater than 10 micron in size is not currently permitted in the WTP WAC, previous testing associated with the EFRT M3 issue resolution demonstrated particles of approximately 30 micron size having a density comparable to plutonium oxide could be suspended and removed from PJM mixed vessels. Future testing with the proposed SHSV will assess the capability of this vessel design to mix and remove particulate material representing 100 micron diameter plutonium oxide.

Heavy Plutonium Particulate and Large Uranium Particles Proposed Control Strategy

As discussed previously, the current criticality controls for WTP were not derived for waste containing HPP. Thus, additional criticality controls are required at WTP prior to this waste being processed. To resolve this issue, a criticality safety evaluation was performed to develop a proposed set of criticality controls. Based on the bounding safe mass limit (approximately 2.7 kg) derived for the idealized HPP geometry (fluted horn) and a set of conservative waste delivery and processing assumptions, the CSE-ES concluded that the conceptual SHSV design can safely process 13 of the 16 Hanford waste tanks containing HPP. The number of tanks that could be processed may be modified based on future evaluation of implementable controls.

As a future action the CSE-ES proposed control strategy will be further developed during design and safety basis finalization. If required, alternate control/process strategies (e.g., direct feed to high-level waste) will be evaluated.

The CSE-ES and the Preliminary CSER also conclude that large uranium particles (i.e., sodium diuranate) are adequately controlled with the current criticality control set (enrichment limit) with no dependence on particle size. ORP has also agreed with this conclusion, as stated in the 2010 letter to the DNFSB (Section 2.1.1, Reference 6)

ORP requested the DOE Nuclear Criticality Safety Program CSSG to independently review the proposed control strategy presented in the CSE-ES. ORP also requested that the CSSG provide perspective and guidance on incorporation of HPP into the WTP design basis. The CSSG review of the CSE-ES (Reference 38) concluded that the proposed control set was reasonable if an effective mass control process could be developed. The CSSG also recommended that other control options could be evaluated as design proceeded, which included:

- Demonstrating by testing that physical mechanisms (e. g. hydraulic equivalence) will preclude all of the HPP from settling independent of the co-precipitated materials thereby likely removing the hazard
- Sending HPP tank wastes directly to the High-Level Waste Facility where there are no PJMs to loft and create the potential for larger masses to loft/settle in unfavorable geometries
- Considering if sufficient caustic boron poison can be added at the HTF to mitigate the HPP risk at the WTP
- Considering using the reduced requirements available in ANSI/ANS-8.10 (Reference 37), if no other control strategy proves available and if the mission consequences of a higher risk criticality event are acceptable.

Waste Sample for Criticality Controls

The CSE-ES concurred with the DNFSB concern that the small volume of HPP present in the waste introduces uncertainty into the representative nature of sample measurements intended to quantify HPP masses (e.g., the autosampling system). Additionally, the DNSFB asserted "if the (high-solid process) vessels are not well mixed, samples drawn from the vessels to ensure that such an event does not occur will not be representative." Consequently, the CSE-ES does not propose controls that rely upon HPP measurements or mixing; instead, one of the proposed controls rely on process based conservative estimates of HPP that could accumulate in the Pretreatment Facility. The accumulation estimate used in the CSE-ES was based on the estimates provided in Reference 9. Final control parameters will be based on HTF batch processing strategy and future waste characterization information.

With respect to co-precipitated plutonium and uranium containing waste, as stated in the DNFSB's *26th Annual Report to Congress* (Reference 2), WTP will rely on sampling at HTF to ensure compliance with the WTP WAC (Reference 4). Further development of the control strategy will occur following assessments of HTF waste feed staging outcomes.

Separation of Fissile Material from Neutron Absorbers

With respect to the DNFSB concern that "Dense particles rich in plutonium and uranium are expected to settle preferentially on the bottom of tanks. These settled particles may form a sediment layer with sufficient fissile mass in a geometry such that a criticality accident is credible." the WTP CSER evaluated normal, bounding normal, and contingent conditions that could occur in WTP (Sections 6 and 7 of Reference 3). This includes conditions that had the potential to separate neutron absorbers from co-precipitated plutonium containing waste (Section 5.4 of Reference 3) and concluded "criticality is not credible during waste processing in the WTP facility."

This conclusion is based on all three chemistry reports (Reference 21–23) evaluating WTP processes, effects influencing plutonium, absorber interactions, and distributions in routine and upset WTP operations waste composition. This conclusion was approved by ORP in Reference 34.

In reference to the HPP, the CSE-ES (Reference 28) assumes that HPP will preferentially settle and accumulate at the bottom of high-solids process vessels. The CSE-ES evaluated several HPP geometries that could form during vessel operation. These geometries included a settled layer forming a lens shape at the bottom of the vessel and an idealized geometry (worst case) in the form of a fluted horn based on all SHSV PJMs in synchronous operation. Calculated safe masses vary significantly between these configurations. However, the CSE-ES proposed a control strategy that applies this worst case (fluted horn) safe mass limit, use of soluble neutron poisons, and inventory control/heel removal to implement the double contingency principle to ensure subcritical conditions in WTP vessels. Neither mixing nor sampling is credited for this control strategy.

Conclusion

ORP considers that the criticality safety concern identified by the DNFSB is resolved based on completion of the following actions:

- Assessments to estimate the mass, particle size, and location of HPP in the HTF.
- Chemistry studies, criticality calculations, and hazards analyses demonstrating that the co-precipitated plutonium waste form can be safely processed in WTP.
- Engineering study with supporting analyses that identifies proposed controls for treatment of waste containing HPP in the Pretreatment Facility.
- Identification of proposed controls identified in the WTP CSER and the CSE-ES for management of tanks wastes containing fissile material, considering both uranium and plutonium.

- Independent review by the DOE Nuclear Criticality Safety Program CSSG on the proposed control strategy for treatment of HPP containing wastes.
- Deliver waste feed to the WTP that complies with the design basis.
- Evaluation of an improved PJM vessel design that will improve mixing performance and the ability to effectively remove heavy solids.

ORP will continue to complete final design and safety basis development of the WTP to fully close the criticality issue.

Concurrence

11-17-16	
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Approval

11/21/2016	
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**Resolution of Defense Nuclear Facilities Safety Board Issues:
Hydrogen in Piping and Ancillary Vessels**

Statement of Issue

The potential for combustible gas generation (principally hydrogen) and ignition in Waste Treatment and Immobilization Plant (WTP) piping is a recognized hazard that must be addressed by both the facility design to ensure mission success and the safety basis to ensure protection of the workers and the public. The project approach for doing so has evolved eliminating, with appropriate technical justification, early conservative assumptions judged detrimental to facility operability and unnecessary to address the piping hydrogen hazards. Technical questions remained however, regarding the interface between new design methodology and the safety analysis to ensure compliance with applicable U.S. Department of Energy (DOE) requirements. Specifically, the role, if any, that probabilistic modeling in the design tools would perform in the safety analysis remained to be clarified.

This hydrogen in piping and ancillary vessel (HPAV) issue is reflected in the Defense Nuclear Facilities Safety Board's (DNFSB) *26th Annual Report to Congress* (Reference 1), which reported the following:

> Hydrogen in Pipes and Ancillary Vessels—Flammable gases generated by the wastes treated in WTP will accumulate in process piping whenever flow is interrupted and in regions that do not experience flow, such as piping dead legs. This hazard, if not properly addressed, may result in explosions and releases of radioactive material within the facility. The WTP contractor is performing a deterministic analysis to establish whether safety controls will be required for this hazard. Also, the WTP contractor is using a probabilistic risk assessment[1] for the design of process piping.

U.S. Department of Energy Resolution of Issue Summary

Liquid high-level radioactive waste stored at the Hanford tank farm produces hydrogen by radiolysis and thermolysis. If a sufficient concentration of hydrogen accumulated in the WTP pipes or vessels and mixed in the right proportions with an oxidant, and an ignition source is present, the gas mixture could ignite. In some cases, the burning gas (deflagration) could transition to a more severe detonation event. Hydrogen gas hazards in vessels differ significantly from those in piping due to the vessels much larger volumes and the usual presence of oxygen in the vessel headspace. The WTP design prevents hydrogen combustion events in vessels, including ancillary vessels like the pulse jet mixers, using active controls (purges and vents) that

[1] The appropriate term should be "quantitative risk analysis." The quantitative risk analysis is a probabilistic software model developed by Bechtel National, Inc. and used to define a robust envelope of hydrogen deflagration and detonation events for use in the design of each piping route in Waste Treatment and Immobilization Plant facilities. The model is a design tool not being used directly in safety analysis as discussed further in this report.

limit gas concentration below the lower flammability limit. Thus, this HPAV design issue is focused only on the piping systems.

The postulated unmitigated effects of hydrogen combustion events include various possible confinement piping system failure scenarios resulting in any of the leak accidents bounded by the safety analysis. Piping boundary failure in black cells or hard-to-reach areas would also jeopardize the facility mission due to the limited access for repair. A piping system failure in the hot cell is considered repairable, but frequent failures in the hot cell could also jeopardize the facility mission.

A previously accepted design approach to manage the accumulation of hydrogen in piping systems where the HPAV event could cause the piping material to exceed the elastic strain limit relied on (1) the passive pipe/component boundary where it could be shown that the resulting strain remained below the elastic strain limit, or (2) active controls (e.g., purge, flush, vent).

In 2010, the WTP Project revised this design approach to:

- Modify the methodology for calculating the loads and strains resulting from an HPAV event for piping up to 4 inches (nominal pipe size [NPS])
- Revise the allowable strain acceptance criteria to allow limited plastic deformation only for hot cell piping up to and including 4 inches NPS
- Always require active controls (i.e., eliminate the use of a strain criteria) for piping greater than 4 inches NPS.

This revised design approach also incorporated the understanding that HPAV events in austenitic stainless steel piping do not have the potential to cause fragmentation, which could damage nearby components. Appropriate material selection controls were established to preclude fragmentation. This updated WTP safety design strategy continues to assure that the piping and inline component primary confinement function is not adversely affected by postulated HPAV events.

The 2010 design approach did not, however, define the role of the new piping design tool in the safety analysis. The design tool employed probabilistic analysis methods, not previously used in safety analysis. DOE developed and issued DOE-STD-1628-2013, *Development of Probabilistic Risk Assessments for Nuclear Safety Applications* (Reference 2), in part to guide the use of the design methodology in the nuclear safety strategy should that approach be chosen. The project has instead elected to develop the required safety basis without reliance upon the design approach as part of the safety analysis in a role that would invoke applicability of this standard.

The WTP safety design strategy has been and remains based on design to assure that the piping and inline component primary confinement function is not adversely affected by postulated hydrogen events. DOE O 420.1B, *Facility Safety* (Reference 3), requires WTP piping systems that contain radioactive waste to be designed to applicable code requirements, namely ASME/ANSI B31.3, *Process Piping* (Reference 4). The code does not explicitly address hydrogen combustion events, but it requires the designer to address such loads using methodology that has been accepted by the DOE Office of River Protection (ORP), the facility owner. As discussed further below, these conditions have been met for WTP's HPAV design methodology.

To further clarify this design approach, the code-based design is judged sufficient to ensure mission success for WTP; the hydrogen-specific methodology, including its probabilistic component, has been accepted by DOE as the owner for this purpose. From a nuclear safety perspective regarding the use of this code-based design, two key design assumptions to be protected by technical safety requirements have been appropriately identified: the hydrogen generation rate and the use of non-fragmenting materials. In instances where the code-based criteria for piping to withstand credible hydrogen combustion loads are not met (principally for piping greater than 4-inches NPS for which they are not applicable given limitations of the experimental data), required active controls to ensure hydrogen accumulation does not exceed the piping route capacity to withstand combustion are also to be included in technical safety requirements.

Details supporting this resolution summary are provided below.

Recent Actions to Resolve the Issue

The following recent actions have been completed to support resolution of the HPAV issue:

- Development of a deterministic calculation of bounding pipe volume unmitigated radiological and chemical consequences to establish functional classification for HPAV piping controls (i.e., for piping and piping components external to vessels) consistent with DOE directives and methods. Specifics are:
  - ***Unmitigated HPAV Calculation for Functional Classification***: Bechtel National, Inc. (BNI) developed calculation 24590-PTF-Z0C-H01T-00003, *Unmitigated Consequences for Pretreatment Hydrogen in Piping and Non-Process Vessel Events*, Rev. F (Reference 5) to determine unmitigated dose consequences from postulated hydrogen events for all WTP process streams in piping, charge vessels, and pulse jet mixers.
  - ***Deterministic Unmitigated Consequence Methodology***: BNI selected the use of the trinitrotoluene (TNT)-equivalent method from DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* (Reference 6) with an airborne release fraction and respirable fraction equal to 1 for determining the source term from hydrogen explosions in both vessels and piping. The method has an established precedent in the DOE complex for modeling potential consequences from explosions and converts the mass of hydrogen to an equivalent mass of TNT.
- ***Preliminary Documented Safety Analysis (PDSA) Change Package (CP)***: A PDSA-CP (Reference 7) for proposed changes to the Pretreatment (PT) Facility-specific PDSA, 24590-WTP-PSAR-ESH-01-002-02, *Preliminary Documented Safety Analysis to Support Construction Authorization; PT Facility Specific Information* (Reference 8) was developed. The PDSA-CP incorporates the results from the unmitigated HPAV

consequence calculation and revises the functional classification of hydrogen controls as discussed above.

- ***Basis of Design Change Notice***: A Basis of Design Change was developed to define the design criteria for HPAV events and is based on the work contained in References 9 and 10 for evaluation and analysis of piping.
  - Quantitative risk analysis (QRA) model and accompanied structural analysis consistent with national consensus code ASME/ANSI B31.3 to evaluate the design of piping 4-inch NPS and less (external to vessels) for high energy explosive events to ensure the structural integrity of affected piping (i.e., primary confinement boundary) for the design life of the facility.
  - Design of greater than 4-inch NPS pipe (external to vessels) consistent with ASME/ANSI B31.3 and with the requirement for active engineered controls to limit the accumulation of hydrogen.
- ***Safety Requirements Document (SRD) Revision***: A revision of the SRD, Appendix B and Appendix C.26 (Reference 11 and 12) was performed to align the SRD with the revised Basis of Design criteria.

The recent actions by DOE present a clear distinction in the application of nuclear safety analysis for functional classification of hydrogen controls, and the design of piping using the HPAV design criteria. Based on the primarily low-to-moderate unmitigated radiological and chemical consequences concluded by the deterministic analysis of explosions postulated to cause failure of HPAV affected piping, the PT PDSA has been revised. Most controls previously credited as safety class or safety-significant to prevent releases associated with hydrogen explosions and limit hydrogen accumulation in piping are now identified as providing defense-in-depth for these events. The design criteria for piping to withstand hydrogen combustion events are defined in the WTP Basis of Design (Reference 13), and are no longer included in the PDSA.

Thus, the WTP safety design strategy has been and remains based on design to assure that the piping and inline component primary confinement function is not adversely affected by postulated hydrogen events, but appropriate distinction is made between design and safety basis requirements.

Response by the Defense Nuclear Facilities Safety Board Staff

ORP briefed the DNFSB staff on the deterministic analysis/unmitigated consequence calculation and the proposed revision to the PT PDSA change package for HPAV affected piping. The DNFSB staff provided questions prior to the formal briefings with ORP and BNI. During their onsite visit of October 5, 2016, responses to the DNFSB staff questions were provided to both earlier and later inquiries (Reference 14). A followup meeting was conducted by telephone on November 1, 2016, to address additional questions associated with the October 5, 2016, DNFSB staff review. The specific questions were associated with the following:

- The control strategy for piping sprays initiated by hydrogen explosions in piping.
- How QRA will be used in relation to the safety basis.

- Whether consequences from full accident progressions (e.g., piping sprays initiated by hydrogen explosions in piping) will be combined.

As mentioned above, these additional questions and all previous questions were addressed and provided to the DNFSB staff.

In summary, ORP considers the DNFSB concerns regarding HPAV affected piping resolved based on ORP's recent completed actions described above.

Role of Nuclear Safety and Engineering Design for Hydrogen in Piping and Ancillary Vessels Affected Piping

A deterministic approach for nuclear safety analysis, assuming failure of the pipe at a qualitatively estimated frequency of unlikely, was performed consistent with the requirements in both DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses*, Chg 3 (Reference 15), and ORP updated safety analysis direction (15-NSD-0017, "Contract No. DE-AC27-01RV14136 – Updated Safety Analysis Direction" [Reference 16]).

The deterministic analysis follows the DOE-HDBK-3010-94 (Reference 6), TNT-equivalent method to determine the source term from a hydrogen explosion. BNI has completed the deterministic analysis for the PT Facility piping (Reference 5), and the results are included in a revision to the PT PDSA (Reference 7).

The unmitigated radiological and chemical consequences (deterministic analysis results) to the public were low for all hydrogen in piping explosions. Radiological and chemical consequences to the co-located worker (CLW) were low for all but a limited number of pipe routes; and a high radiological consequence was determined for one pipe route (waste stream CNP10) after 1,500 continuous hours of stagnant flow conditions and associated hydrogen generation. Several waste streams analyzed resulted in moderate chemical consequences to the CLW after 5,000 hours of hydrogen generation (i.e., CNP10, HLP09, TLP02, and FEP19). The unmitigated consequences to the facility worker were qualitatively estimated as high in the hazards analysis for all piping hydrogen explosions in the PDSA.

Based on these consequences, no controls for piping specific to HPAV events are required for protection of the public. Therefore, there are no safety class piping routes for the HPAV events. Protection of the CLW is provided by the C5 confinement boundary to contain the release, and the C5 ventilation system to filter particulates from any pipe breach and elevation and dispersion of any unfiltered chemical constituents. The facility worker is also protected by the C5 confinement boundary, in conjunction with cascading airflow provided by the ventilation system. ORP considers these credited controls adequate and justifiable for workers based on the unmitigated dose consequences.

Most controls to limit hydrogen accumulation in the piping are retained in the design and are identified in the PDSA as providing defense-in-depth. Generally, these defense-in-depth features that include pipe flushing as part of operational procedures are required to ensure efficient operation of the facility.

The PDSA revision also identifies hydrogen explosions in piping as a potential initiator for the bounding pipe spill and spray accidents. Functional requirements and performance criteria associated with the piping's ability to withstand hydrogen explosion loads have been added to the spill and spray accidents in Chapter 3.0 and the piping design requirements in Chapter 4.0 of the PDSA. Requirements for active controls to limit accumulation of hydrogen in piping that cannot meet the passive performance criteria will be included in these same sections as directed by a condition of approval in the Safety Evaluation Report (SER) (Reference 17). Functional classification of these controls is at the same level as the pipe they are supporting. As described above, piping less than or equal to 4-inch NPS will generally not require active controls. Only approximately 5 percent of the process piping in the PT Facility is expected to be larger than this.

Use of Quantitative Risk Analysis for Hydrogen in Piping and Ancillary Vessels Affected Piping

ASME/ANSI B31.3 does not provide explicit design guidance for high energy explosion events such as those postulated for HPAV affected piping. The provisions of ASME/ANSI B31.3, paragraph 300, do provide for applying more rigorous analysis when the existing code requirements are not adequate with the provision that validity of such analysis can be demonstrated. For these situations, the owner must approve the approach and the methodology documented in the engineering design. Under this provision, testing and analysis of HPAV affected piping was performed by WTP. A series of deflagration and detonation tests in 2008 and 2009 were undertaken to obtain data to be used in analysis of piping response and impact as a result of hydrogen detonations. Correlations were developed from these tests and documented in the HPAV Engineering Analysis Methods and Criteria document hereafter referred to as the 07-011 document (Reference 10). Finite element analysis (FEA) models were developed to predict the structural response of the piping systems. These results and correlations provide the technical basis for the development of the HPAV analysis methodology and acceptance criteria.

QRA was developed using a probabilistic modeling approach using Monte Carlo calculation methods in order to predict the frequency and severity of hydrogen events over the life of WTP. This included development of extensive fault trees that allows the prediction of hydrogen events analyzing the initiators of events such as equipment failure and human error and other external precursors to creating optimal conditions for a hydrogen detonation and deflagration. The prediction of the type and severity of hydrogen loads from credible events is based on correlations developed from detonation testing.

The QRA software model underwent extensive review and comment resolution by an independent review team consisting of 13 experts whose discipline fields include gas phenomenology, detonation analysis, structural analysis and response, and probabilistic analysis. Additionally, the DNFSB staff were involved and provided numerous comments. All comments and concerns have been satisfactorily resolved.

ORP had not previously determined whether using the QRA model for design rendered it a probabilistic risk assessment tool in nuclear safety analysis. In 2013, ORP requested BNI to develop a Probabilistic Risk Assessment (PRA) plan to address the QRA per DOE-STD-1628-2013 requirements (Reference 2). In 2014, ORP did not accept the proposed PRA plan and instead accepted BNI's decision to ensure a deterministic approach to HPAV safety analysis. BNI's recent submittal of the document, 23490-PTF-Z0C-H01T-00003, Rev. F (Reference 5), established a clear deterministic basis for functional classification of HPAV affected piping. This document is part of the HPAV PDSA-CP (Reference 7) submitted to ORP for approval.

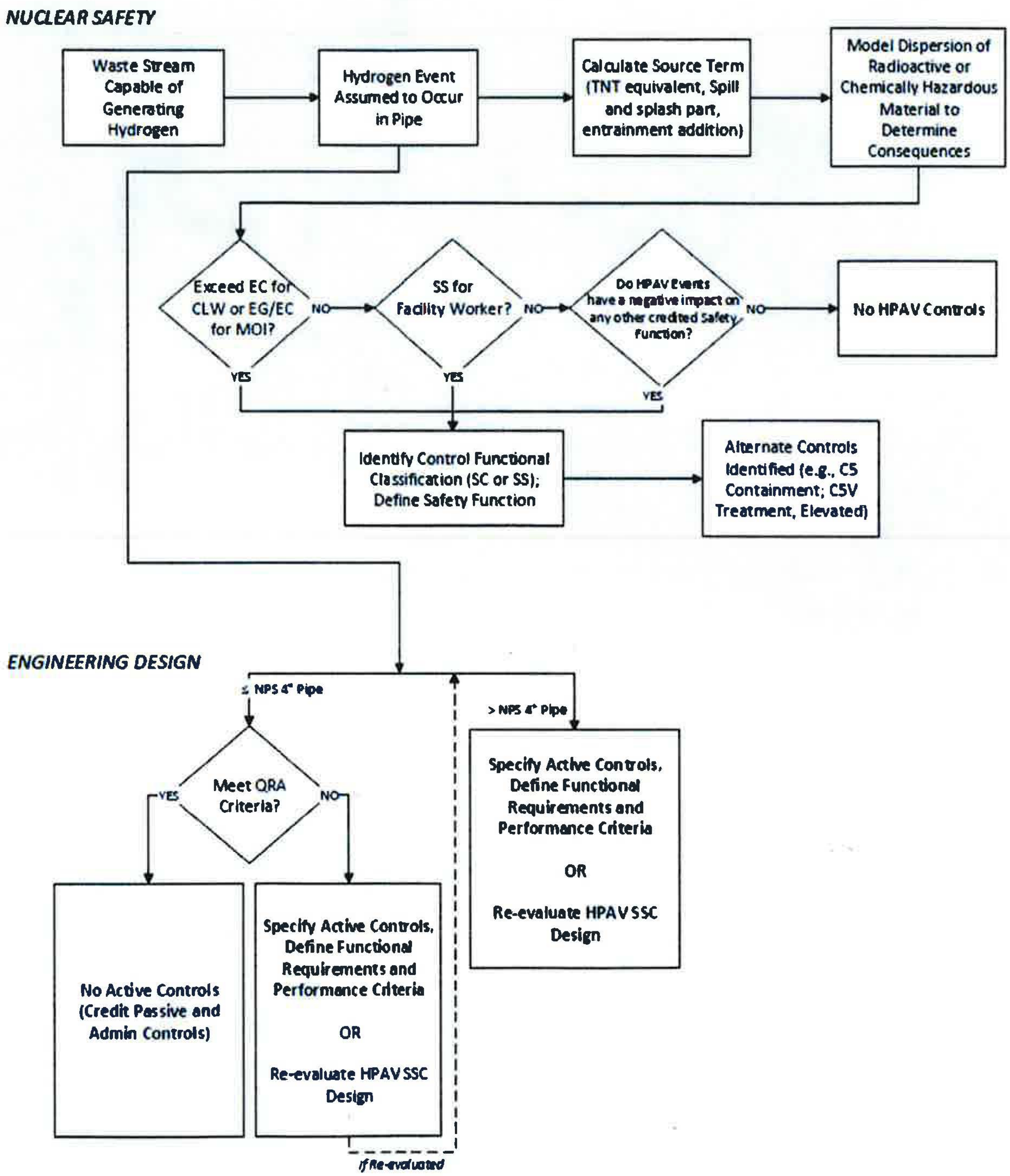
At present, the QRA model is approved as a design tool for establishing a robust set of pipe route specific design loads due to credible hydrogen combustion events.

The HPAV PDSA-CP revised the strategy for deterministically evaluating bounding potential explosions HPAV affected piping and also included hydrogen combustion events as an initiator for other analyzed events (spills and sprays) that may follow an undetected explosion when the facility is restarted. The deterministic evaluation was used as the basis for evaluating functional classification of structures, systems, and components. The basis for functional classification is consistent with accepted methodologies in DOE-STD-3009-94, Chg 3. The PDSA-CP, in conjunction with the *Basis of Design* and SRD changes, provide a better distinction between HPAV affected piping nuclear safety requirements and engineering design requirements.

Discussion of Nuclear Safety Analysis and Engineering Design

Figure 1, shows the nuclear safety and engineering design flowchart for HPAV events process used to evaluate the hazards, select controls, and the utilize the QRA model during the design process.

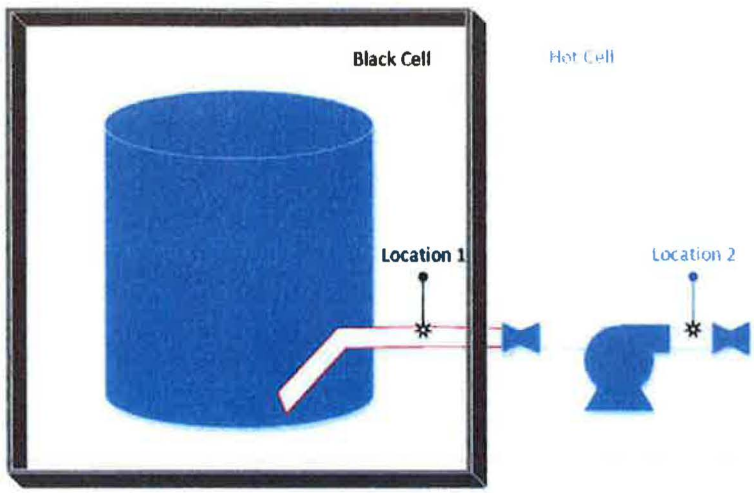
Figure 1. Nuclear Safety and Engineering Design Flowchart for Hydrogen in Piping.



Application of the Revised Nuclear Safety Analysis Methodology to HPAV Affected Piping

Using the conservative TNT-equivalent methodology, quantitatively determined the unmitigated consequences for a hydrogen explosion in piping and included ancillary vessels (Reference 5). Figure 2 illustrates a typical event considered in the analysis.

Figure 2. Piping system Suction line from vessel to pump.



The HPAV-specific consequence analysis assumed the piping (volume of the entire pipe run, to include the dip leg volume) or the nonprocess[2] vessel is completely filled with waste stream material, which then produces hydrogen for 1,000 hours. The resulting hydrogen is assumed to explosively react with a stoichiometric quantity of nitrous oxide (a hydrogen explosion with nitrous oxide produces more reaction energy than an explosion with air). The "TNT Equivalent" methodology as described in DOE-HDBK-3010-94, was then used to determine the amount of waste stream material (the major "source term" contributor) that is aerosolized in the explosion. This was combined with contributions from the spill (splash and splatter) volume and entrainment, to determine the full source term for calculating radiological and chemical consequences.

For conservatism, no resistance to the release of radioactive and/or chemically hazardous material from the pipe is considered. The artificial conditions used are not relatable to other release events, such as vessel spill events or pipe spray release events. It is assumed that the hydrogen event overstresses the piping resulting failure.

Calculations were performed considering 1,000 hours of hydrogen generation, with sensitivity analyses performed out to 5,000 hours. In all cases, for explosions in piping, unmitigated radiological and chemical consequences were determined to be low to the public. At 1,000 hours, unmitigated consequences to the CLW from piping explosions were low except radiological consequences from one process stream (CNP10) and chemical consequences from

[2] "Non-process vessel" is defined in the Pretreatment Facility Preliminary Documented Safety Analysis Change Package as an ancillary vessel.

another process stream (UFP07), which were both moderate. Between 1,000 and 5,000 hours, chemical consequences to the CLW increased to moderate for several streams (CNP10, HLP09, TLP02, and FEP19), and radiological consequences were high for the CNP10 process stream.

Application of Hydrogen in Piping and Ancillary Vessels Engineering Analysis Methods and Criteria

The 07-011 methods and acceptance criteria are applied to design the piping system for the credible loads developed using the QRA. The engineering design methods address the robustness of piping support hangers (which also must withstand the HPAV loads) as well as the piping. Redesign of the piping system (e.g., increased pipe wall thickness or added supports) can be the result when the HPAV load is calculated to compromise the piping system. The safety basis recognizes that the piping and supports are designed in accordance with ASME/ANSI B31.3 as augmented by the 07-011 acceptance criteria for normal or occasional loads (as defined in ASME/ANSI B31.3). In cases where this is not achievable (e.g., NPS greater than 4 inches or when the design cannot meet the 07-011 requirements), active controls to limit the accumulation of hydrogen are required for piping that is designated as safety-significant or safety class. These requirements are part of the performance criteria for the piping (credited in the PDSA for the bounding spill and spray events) in the PDSA-CP.

The QRA process and 07-011 methods and criteria are used in design of piping systems and the related design requirements and criteria are established in the Basis of Design, Appendix C (Reference 13), and the Safety Requirement Document (SRD) Volume II, Appendix B and Appendix C.26 (Reference 12).

Piping is broken into three categories as part of the design approach:

1. Negligible hydrogen production (Category 1): No HPAV controls required.
2. Significant hydrogen production in piping NPS 4 inches and below (Category 2): Detonation analysis is performed on the limiting pipe geometry to bound all other NPS 4-inch piping and ensures that the pipe will not fail per the criteria defined in the 07-011 (Reference 10) report. When applicable deflagration analyses are also required and may be sufficiently frequent to require treatment as normal (not occasional) loads. The piping is treated like greater than NPS 4 inches (see below) if failure is not precluded by design.
3. Significant hydrogen production in piping larger than NPS 4 inches (Category 3): Active controls are established for all large diameter piping to limit the hydrogen accumulation. Also, included in Category 3 are NPS 4-inches and smaller piping systems that cannot meet the criteria in 07-011.

The HPAV engineering analysis methods ensure piping segments designed for hydrogen combustion loads are robust to assure structural integrity for the design life based on extensive testing.

Conclusion

The WTP safety design strategy has been and remains based on design to assure that the piping and inline component primary confinement function is not adversely affected by postulated hydrogen events. DOE O 420.1B requires WTP piping systems that contain radioactive waste to be designed to applicable code requirements, namely ASME B31.3. The code does not explicitly address hydrogen combustion events, but it requires a capable designer to address such loads using methodology that is accepted by DOE. As discussed in this resolution record, these conditions have been met for WTP's HPAV design methodology.

Specifically, the role of the QRA is restricted to piping design and is not used in nuclear safety analysis. The design requirements to limit hydrogen accumulation in piping are now included in the WTP SRD. ORP considers the DNFSB concerns resolved based on its recent actions to resolve the issue (1) revision of the HPAV affected piping unmitigated consequence analysis and control strategy resulting in the approval of the PT PDSA change package as documented in the SER (Reference 17); and (2) approval of the revised SRD (Reference 18).

On the basis of these completed actions, ORP considers the HPAV issue resolved.

Historical Background Enclosure

In April 12, 2002, pipe failures in nuclear power electricity generating stations resulted in the issuance of NRC Information Notice 2002-15, "Hydrogen Combustion Events in Foreign BWR Piping" (Reference 19). This notice was intended to raise concern in the nuclear industry of accumulating detonatable gas mixtures in piping and ensure measures were taken to address this hazard.

In 2003, Bechtel National, Inc. (BNI) began investigations into hydrogen accumulation in piping and ancillary vessels (HPAV) in Waste Treatment and Immobilization Plant (WTP). By 2004, BNI had established an External Guidance Review Team (EGRT) whose charter was to review and approve the BNI developed approach to resolving concerns with hydrogen in piping and ancillary vessels (HPAV).

By 2005, BNI had developed a conservative analysis method referred to as the "Bubble of Concern" (BOC) method for establishing where HPAV controls would be required in the WTP design. BNI had also established HPAV generic solutions for prevention of hydrogen accumulation when the BOC limit could not be met. BNI submitted several ABARs that added controls to prevent accumulation of hydrogen in pipe, and it also recommended that plastic strain up to 15% be allowed as a mitigative safety strategy to minimize the number of active safety controls required.

In April 2006, ORP disapproved allowing up to 15 percent plastic strain and established an acceptance limit of 0.2 percent elastic strain (Reference 20). The U.S. Department of Energy (DOE) also required that an acceptable approach must also assess the structural loading effects of deflagration to detonation transition at the most limiting locations. Work began on developing an acceptable structural analysis approach in 2006 working with DOE's consultant on explosion analysis, Dr. Shepherd of California Institute of Technology.

In May 2007, DOE issued a letter approving two authorization basis approval requests (Reference 21), which included two conditions of approval (COA). COA No. 1 establishes the hydrogen event as a reflected deflagration to detonation transition and COA No. 2 requirement to ensure HPAV affected piping, pipe support, and pipe attachment responses remain elastic (0.2 percent strain or less). By late 2007 progress on developing an acceptable analytical method was hindered by the lack of industry information applicable to WTP piping sizes and configurations. This combined with an increasing number of active controls as a result of applying the new acceptance limit of 0.2 percent elastic strain using the BOC analysis method resulted in an agreement in October 2007 to perform full scale testing. The full-scale testing commenced in 2008. The purpose of the testing was to (1) reassess the conservatisms of the BOC method, (2) provide test information that would directly support WTP conditions, and (3) development of a revised analysis method.

HPAV Assessment Team: DOE chartered a HPAV Assessment Team to look at the design and safety approaches being considered for WTP and reassess the allowable strain criteria. The HPAV Assessment Team was chartered and met January 28 and 29, 2009. On February 26, 2009, the team issued its final report on Alternate Evaluation and Design Approach for HPAV

(Reference 22) that recommended use of quantitative risk analysis (QRA) methods and additional testing on larger diameter piping.

Following the issue of the HPAV Assessment Team's report, multiple interfaces with the Defense Nuclear Facilities Safety Board (DNFSB) occurred starting with a briefing at DNFSB Headquarters on April 15 and 16, 2009. The staff was briefed on the conclusions of the HPAV assessment report, plans for implementation of the assessment team recommendations, remaining testing required to support QRA development, and how the QRA was to be developed and used. DNFSB issued Recommendation 2009-01 on July 30, 2009, advising DOE of the need for adequate policies and associated standards and guidance on the use of QRA methodologies at DOE defense nuclear facilities.

Operational Review Team: DOE chartered an Operational Review Team to provide a more detailed response to concerns that the number of proposed HPAV active controls resulted a level of operational complexity that made compliant operation especially challenging and failed to afford a real safety benefit commensurate with the effort required. The team consisted of senior industry experts from DOE facilities with extensive experience in safety practices and control selection. The Operational Review Team issued its report on July 29, 2009, concluding that HPAV control strategy simplification was warranted and would (1) result in significant advantages in operability, maintainability, and constructability; (2) result in fewer distractions for the operators and less radiation exposure for the workforce during facility operations; and (3) provide improvements in overall reliability and safe operation.

The HPAV test programs and development of the QRA continued through 2009 and consistently demonstrated that actual piping systems did not fail during hydrogen combustion events. The testing supported mechanistic understanding of the various structural loading mechanisms that needed to be addressed for different types of combustion events, possible initial conditions, and upon completing the testing, finite element correlations, and preliminary software development, the processes and criteria were reviewed by a DOE Peer Review Team (PRT) and the DNFSB staff, in December 2009. Following these reviews, BNI submitted basis of design and SRD change notices to the DOE Office of River Protection for approval of the HPAV methodology. DOE approved the HPAV basis of design changes and the SRD changes in February 2010 (References 23 and 24).

The DNSFB also communicated other concerns associated with the HPAV testing program as related to flow-down of quality assurance to subcontractor (Reference 25):

> May 5, 2010
>
> BNI did not impose the quality assurance requirements cited in the Department of Energy (DOE) Order 414.1C, Quality Assurance, upon Dominion Engineering Incorporated (DEI), BNI's subcontractor for HPAV test program. Consequently, DEI and its subcontractor did not use the order's quality assurance requirements, including those related to safety software, for the HPAV test program. This challenges the reliability and usefulness of the data resulting from the test program in demonstrating the safety of this aspect of the HPAV design.

> BNI did not properly implement the quality assurance requirement of NQA-1 2000, Part I, for the HPAV test program, and, BNI has only required its subcontractors to meet the basic paragraph for the application of Part I requirements (Paragraph 100, Basic), which does not provide the rigor necessary to ensure quality of work.

And concerns associated with the independent review of the HPAV criteria (Reference 26):

> May 12, 2010
>
> Based on the briefing, however, the Board believes that DOE should seek to strengthen the review's emphasis on safety and to ensure that it delves into BNI's final criteria and methods in sufficient detail.
>
> The charter directs the review team to answer specific questions regarding (1) assurance that a hydrogen event would not interfere with safety functions of systems, structures, and components; (2) assurance that a hydrogen event would not significantly affect the duration of WTP's mission; and (3) the effects of other flammable species that might exist at WTP.
>
> The Board's concern extends beyond operability. The scope of the review should emphasize an evaluation of whether the technical bases for the design approach and acceptance criteria are technically sound and robust, and that they achieve DOE's safety objectives. This includes evaluation of the unique analytical methodologies specified to develop the response of piping and components to a hydrogen deflagration or detonation the testing accomplished to support the design, testing plans to qualify piping and components, and the quantitative risk analysis.
>
> The Board believes preserving the independence of the review team is paramount. The committee's final product would be enhanced, however, if the review met the charter's original intent, which focused on both safety and reliability, and if the schedule provided adequate time to account for the magnitude and complexity of the documentation supporting the safety design strategy.

QRA Peer Review Team: DOE chartered a QRA PRT led by Brookhaven National Laboratory probabilistic risk experts to review the QRA processes and development efforts. The scope of the review focused on whether the QRA was conducted in accordance with the industry conventions for performing risk assessments and whether the resulting model and data inputs were appropriate to serve the intended purpose of the QRA (i.e., support evaluation of the adequacy of the piping design to meet code requirements). The review concluded that for the state of development of the QRA at the time, the systems' modeling appeared to be reasonable. The PRT commended BNI for its innovative use of QRA techniques in the construction of the QRA model, but noted that model changes were necessary of which the most important was application of probabilistic distributions on failure rates. These comments were all addressed by the final model. The DOE Health Safety and Security QRA PRT issued its final report, *Peer Review of Waste Treatment Plant Quantitative Risk Assessment of Hydrogen Events in Piping and Vessels*, on May 28, 2010 (Reference 27).

HPAV Independent Review Team: The DNFSB's quarterly letter to Congress of April 15, 2010, highlighted that they recommend DOE charter a HPAV Independent Review Team (IRT) to review HPAV and QRA processes. The HPAV IRT was assembled in March 2010 and consisted of 13 experts with a combined industry experience of 450 years spanning the range of technical disciplines of gas phenomenology, detonations analysis, structural analysis and response, and probabilistic analysis. Their charter was to answer specific questions regarding (1) assurance that a hydrogen event would not interfere with safety functions of systems, structures, and components; (2) assurance that a hydrogen event would not significantly affect the duration of WTP's mission; and (3) the effects of other flammable species that might exist at WTP. A briefing of the DNFSB on the HPAV IRT charter resulted in a follow up letter from the DNFSB to DOE Office of Environmental Management in July 2010 (Reference 28 and 29), which relayed the DNFSB's concern as extending beyond operability as:

> The scope of the review should emphasize an evaluation of whether the technical bases for the design approach and acceptance criteria are technically sound and robust, and that they achieve DOE's safety objectives. This includes evaluation of the unique analytical methodologies specified to develop the response of piping and components to a hydrogen deflagration or detonation the testing accomplished to support the design, testing plans to qualify piping and components, and the quantitative risk analysis.

Multiple briefing sessions on the HPAV QRA processes, testing, and calculations were held to review the documentation, with DNFSB staff members in attendance for every HPAV IRT review meeting. The HPAV IRT issued its report of findings and recommendations on July 12, 2010, with Rev. 1 issued on August 10, 2010 (24590-CM-HC4-W000-00182-01-0001-00001). The IRT review identified 35 findings and 32 recommendations (Reference 30) and concluded, that following implementation of the team's findings, there is high confidence that:

1. The QRA approach is acceptable for defining loads to be used in design, and there is a low probability of exceeding either their frequency or their magnitude.
2. The best estimate pipe stresses and strains, computed from the defined loads in the manner proposed by BNI, are not likely to be significantly exceeded.
3. The combination of QRA load definitions, best estimate piping system response calculations and conservative acceptance criteria developed pursuant to the piping Code B31.3 provides a reasonable balance of probabilistic and deterministic elements appropriate for design of HPAV piping and components.
4. The net result of this approach to design will be a low probability of pipe failure if hydrogen explosions occur.

DNFSB Holds Public Hearing on HPAV: While continuing to resolve the HPAV IRT findings and recommendations and implement new NQA-1 software requirements, BNI prepared responses to support a DNFSB public hearing to be held on October 8, 2010. No new concerns were raised at the hearing.

HPAV IRT Issues Final Report: BNI completed resolution of all HPAV IRT findings and recommendations by July 2011 and provided documentation of all changes. Briefings of the changes and updated processes were presented through multiple meetings, which included DNFSB staff attendance. Responses to all the findings and recommendations were accepted by the IRT, which issued its final report on January 5, 2012, *Hydrogen in Piping and Ancillary Vessels in the Pretreatment Facility of the Hanford Waste Treatment Plan, Final Report by and Independent Review Team* (Reference 31). Following issue of the IRT report, DOE's detonation consultant raised questions in February 2012 that required additional analysis and justification. Responses to these questions were also completed to the satisfaction of DOE closing all outstanding questions regarding the validity of the processes for dealing with hydrogen events at WTP.

DOE HPAV QRA Analysis Surveillance: Between February 2012 and June 2013 DOE conducted surveillance S-13-NSD-RPPWTP-004, *Review of Bechtel National Incorporated (BNI) Implementation of Hydrogen in Piping and Ancillary Vessels (HPAV) Quantitative Risk Analysis (QRA) Process* (Reference 32), on route 18 of Pretreatment Facility, which is the transfer route from UFP-VSL-00002B to HLP-VSL-00027B. This transfer route is 3-inch diameter schedule 40 piping with one of the highest hydrogen generation rates in Pretreatment Facility. During the surveillance, each process and engineering product were reviewed in detail to ensure they complied with the changes implemented from the HPAV IRT review. DOE completed the surveillance concluded there was sufficient evidence that the QRA implementation process was adequate to support design analysis.

DNFSB 2013 Report to Congress: In July 2013, the DNFSB summarized the open nuclear safety issue of HPAV in their periodic Report to Congress as follows:

> Flammable gases generated by the wastes treated in WTP will accumulate in process piping whenever flow is interrupted and in regions that do not experience flow, such as piping dead legs. DOE has approved a strategy that allows for hydrogen explosions in piping under certain conditions. This strategy relies on a quantitative risk analysis and other complex models to predict the magnitude of the explosion and the response of the piping system. The Board is concerned that DOE has not established how the quantitative risk analysis will be implemented.

DOE-HSS Issues DOE-STD-1628 Development of Probabilistic Risk Assessments for Nuclear Safety Application: In response to DNFSB Recommendation 2009-01 addressing concerns with the need for adequate policies and associated standards and guidance on the use of quantitative risk assessment methodologies, DOE issued DOE-STD-1628, *Development of Probabilistic Risk Assessments for Nuclear Safety Applications*, in November 2013 and the DNFSB followed up with a letter on January 28, 2014, to DOE Office of Environmental Management providing notification that the DNFSB agreed the actions taken by DOE were sufficient and that Recommendation 2009-01 was closed.

The changes made to the HPAV QRA processes as a result of the reviews discussed above are incorporated into the following two WTP reports:

1. 24590-WTP-RPT-ENG-07-011, *HPAV Engineering Analysis Methods and Criteria*, Rev. 7

2. 24590-WTP-RPT-ENG-10-008, *Quantitative Risk Analysis of Hydrogen Events at WTP: Development of Event Frequency Severity Analysis Model*, Rev. 4.

The methods and acceptance criteria of these reports have been codified in the proposed Basis of Design Change Notice, 24590-WTP-BODCN-ENG-15-0005 and the revised Safety Requirements Document (SRD).

Concurrence

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Frederick B. Hidden, Nuclear Safety Engineer, Nuclear Safety Division, Office of River Protection — Date: 12/16/16

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Langdon K. Holton, Senior Technical Authority, Waste Treatment and Immobilization Plant, Office of River Protection — Date: 12/16/16

Approval

Robert G. Hastings, Assistant Manager, Technical and Regulatory Support, Office of River Protection — Date: 12/16/16

William F. Hamel, Federal Project Director, Waste Treatment and Immobilization Plant, Office of River Protection — Date: 12/17/16

Kevin W. Smith, Manager, Office of River Protection — Date: 12/17/16

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1. DNFSB 2016, *26th Annual Report to Congress*, Defense Nuclear Facilities Safety Board, Washington, D.C., March.

2. DOE-STD-1628-2013, *Development if Probabilistic Risk Assessments for Nuclear Safety Applications*, DOE Standard, U.S. Department of Energy, Washington, D.C.

3. DOE O 420.1B, *Facility Safety*, U.S. Department of Energy, Washington, D.C.

4. ASME/ANSI B31.3, *Process Piping*

5. 24590-PTF-Z0C-H01T-00003, *Unmitigated Consequences for Pretreatment Hydrogen in Piping and Ancillary Vessel Events*, Rev. F, Bechtel National, Inc., Richland, Washington.

6. DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, U.S. Department of Energy, Washington, D.C.

7. CCN: 290777, 2016, "Contract Deliverable 9.1 – Preliminary Documented Safety Analysis Change Package 24590-PTF-PDACP-NS-15-0004, Proposed Changes to the Preliminary Documented Safety Analysis to Support Construction Authorization; Pretreatment Facility Specific Information" (External Letter to W.F. Hamel, U.S. Department of Energy, Office of River Protection), from L.W. Baker, Bechtel National, Inc., Richland, Washington, July 29.

8. 24590-WTP-PSAR-ESH-01-002-02, *Preliminary Documented Safety Analysis to Support Construction Authorization; PT Facility Specific Information*, Bechtel National, Inc., Richland, Washington.

9. 24590-WTP-RPT-ENG-10-008, *Quantitative Risk Analysis of Hydrogen Events at WTP: Development of Event Frequency Severity Analysis Model*, Rev. 4, Bechtel National, Inc., Richland, Washington.

10. 24590-WTP-RPT-ENG-07-011, *HPAV Engineering Analysis Methods and Criteria*, Rev. 7, Bechtel National, Inc., Richland, Washington.

11. CCN: 280343, 2016, "Supersedes CCN: 287650 – Contract Deliverable 3.3(A) – Transmittal of Changes to 24590-WTP-DB-ENG-01-001, Rev. 3, *Basis of Design*; and Regulatory Deliverable 9.1 – Transmittal of Changes to 24590-WTP-SRD-ESH-01-001-02, Rev. 8, *Safety Requirements Document Volume II*" (External Letter to W.F. Hamel, U.S. Department of Energy, Office of River Protection), from L.W. Baker, Bechtel National, Inc., Richland, Washington, October 3.

12. 24590-WTP-SRD-ESH-01-001-02, *Safety Requirement Document Volume II*, Rev. 8, Bechtel National, Inc., Richland, Washington.

13. 24590-WTP-DB-ENG-01-001, 2015, *Basis of Design*, Rev. 3, Bechtel National, Inc., Richland, Washington, December 11.

14. CCN: 293461, 2016, Meeting Minutes, Defense Nuclear Facilities Safety Board Staff Meeting, October 26.

15. DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses*, Chg 3, U.S. Department of Energy, Washington, D.C.

16. 15-NSD-0017 (CCN: 281177), 2015, "Contract No. DE-AC27-01RV14136 – Updated Safety Analysis Direction" (External Letter to M. McCullough, Bechtel National, Inc.), from R.L. Dawson and K.W. Smith, U.S. Department of Energy, Office of River Protection, Richland, Washington, June 29.

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18. 16-WTP-0216, 2016, "Approval of Changes to the Safety Requirements Document Addressing the Engineering Approach for Hydrogen in Piping and Ancillary Vessels" (External Letter to J.M. St Julian, Bechtel National, Inc.), from K.W. Smith, U.S. Department of Energy, Office of River Protection, Richland, Washington, December 17.

19. NRC Information Notice 2002-15, "Hydrogen Combustion Events in Foreign BWR Piping," Washington, D.C., April 12, 2002.

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21. 07-WTP-114 (CCN: 157257), 2007, "Contract No. DE-AC27-01RV14136 – Approval of Authorization Basis Amendment Requests (ABAR) 24590-WTP-SE-ENS-05-0076, Revision 0, "Acceptance Criteria for Hydrogen Explosions in Piping and In-Line Components," and 04-0197, Revision 0, Implementation of Revised Time Basis for Single Failure Criteria for Hydrogen Mitigation" (External Letter to W.S. Elkins, Bechtel National, Inc.), from S.J. Olinger, U.S. Department of Energy, Office of River Protection, Richland, Washington, May 10.

22. CCN: 201897, 2009, *WTP - Control of Hazards Associated with Hydrogen Accumulation in Piping and Ancillary Vessels - Alternative Evaluation and Design Approaches, HPAV Assessment Team Report for DOE-ORP*, February 26.

23. 10-WTP-047 (CCN: 214662), 2010, "Contract No. DE-AC27-01RV14136 – Approval of Basis of Design Change Notice (BODCN) 24590-WTP-BODCN-ENG-10-0001, HPAV Analysis and Design Criteria" (External Letter to R.W. Bradford, Bechtel National, Inc.), from G.A. Girard, U.S. Department of Energy, Office of River Protection, Richland, Washington, February 24.

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